PROBLEM SOLUTION OF THE DRIVE SYSTEMS' FREQUENCIES COMPATIBILITY WITH THE DRILLING RIGS' DYNAMIC PARAMETERS

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Abstract. The quick-acting functioning theory of drilling rigs automated electric drive is proposed. The control object's frequency peculiarities of the drilling rig drives are investigated. The dynamic compatibility task of the drive frequency characteristics with the characteristics of multi-mass mechanisms with lumped and distributed parameters with changed addition masses is decided. The neuro-fuzzy control's ideas for the oscillation suppression in control system are used.

Introduction. Technical standard of drive systems with high requirements for static and dynamic control modes are common industrial drives with active correction and two-loops control systems through the channels of the speed and excitation as DC motors as well AC ones [1, 2, 3].

The control technology with complicated dynamic objects on basis automated electric DC and AC drives with the characteristics consecutive correction occupies important place in modern approach to the optimization of the machines and installations dynamic work modes [4, 5]. A characteristic feature for such systems is presence thyristor rectifier for DC drive and voltage transistor autonomous inverter with amplitude-pulse modulation for AC drive, and likewise special transmissions which transmitting torque from engine to executive device. At the same time masses and the elasticity of the separate links of mechanical system can be as lumped and as well distributed (drilling rigs, excavators, band conveyors, mine winder installations and etc [6, 7, 8]. Such objects control due to the large masses have low natural frequencies. DC drive systems due to the inertia of the thyristor converter and mechanical inertia of the motor armature are a low pass filters with a good quality factor and a bandwidth of up to 50 rad/s. AC drive systems due to low mechanical inertia of the motor and higher frequency PWM switching impulse of the modulator to have a bandwidth of up to 200 rad/s. Therefore, the modernization of the electric drive system with the replacement of the DC system in AC one, greatly changes the dynamics of the entire electromechanical installation [9].

The problem formulation. Using the method of active consecutive correction and ideas of fuzzy control will finding loop's additional corrective regulators which suppress the influence of the transmission elastic properties in the control system dynamics.

Materials under analysis. Additional dynamic elements which have conditioned by presence of the transmission elastic properties, are describing by fractionally rational functions with high degrees [10, 11]. The characteristic frequency values of additional transfer function are less than the corresponding control loop cutoff frequency. The generalized structural scheme of control object has presented in the form of transfer functions of the object control compensated part $W_{okn}(s)$ and the transfer functions of the control object noncompensated part which due to the elastic properties of the transmission and written as a fractionally rational function $\Sigma a_{mn}/ \Sigma b_{mn}$.

In researched drive systems each parameter control loop (coordinates) generally contains, as a rule, not only one "big" time constant that compensated by the action of the regulator, but also a fractionally rational function with time constants, which comparable with single out "big" time constant, that greatly complicates the synthesis system and does not allow to use the same type of control algorithms used in general industrial drives.

The control object structurally broken up into two units which compensated and noncompensated by classic controller parts. The compensated part is chosen in the form of the dynamic unit that not exceeding second order with one obviously expressed "big" time constant. Then the processes in the circuit is effectively corrected by the classic controller with PID (proportional-integral-differential) characteristics, or obtained from this characteristic (PI - proportional-integral, PD - proportional-differential, P - proportional, I - integral).

The sought-for control laws of researched electric drives are defined by technological singularities with the restrictions imposed on the parameters of the electrical and mechanical parts of the drive system. Restrictions have imposed on the parameters of the mechanical energy flow, of the acceleration and jerk magnitudes permitted transmission, the overload capacity of the engine, its permissible heating, etc. These factors combined with the types of the perturbation have determined allowable laws change as the external (output) as well and all the intermediate (internals) coordinate system of the drive. Definition of classical algorithms functioning regulators performed by sequential correction of the dynamic characteristics of each loop taken separately, beginning from the maximum fast-acting – the internal $m = 1$, up to the outer loop $m = n$ with a minimum fast-acting. Under optimizing understood the adduction of dynamic parameters of the closed loop in accordance with the limitations imposed on the quality of the transition process.

The generalized transfer function of the object optimized loop under the assumptions made is presented to the form

$$W_{on}(p) = W_{okn}(p) \cdot W_{onn(p)} = \frac{2 \cdot \xi_n' \cdot T_n' \cdot s + 1}{T_n^2 \cdot s^2 + 2 \cdot \xi_n \cdot T_n \cdot s + 1} \cdot \frac{\sum a_{mn} \cdot s^m}{\sum b_{mn} \cdot s^m}, \tag{1}$$

where T_n, T_n^1 – time constants, ξ_n, ξ_n^1 – damping coefficients.

Here dynamic unit $W_{okn}(s)$ corresponds to the loop's parts, the effect of which is compensated by classic controller. The second dynamic unit is fractionally rational expression, actions of which due to the complicated of the algorithm compensation cannot be suppressed by the classical PID regulator. If to attribute the time constants of fractionally rational transfer functions to the "small" non-compensated time constant loop, its fast-action significantly reduced. The latter circumstance would adversely affect the fast-action of the entire control system. The choice of a "small" uncompensated time constant of the optimized control loop is determined by the allowable limit of speed loop fast-action.

To suppress the elastic vibrations into the transmission line may include additional regulated unit in parallel to the main unit of the regulators (distributed additional classic regulators) or recalculate action of parallel additional regulators to the input of the semiconductor converter - the output of the current regulator (concentrated classical regulator). The latter is preferable, as the corrective action is input to the fastest loop. The algorithms work for such mode suppression by regulators vibrational process in the control system are defined as follows.

For compensation the additional transfer functions in the series with classic regulator included an additional controller with the transfer function

$$W_{n(}(s) = \Sigma b_{mn} s^m \; \Sigma a_{mn} s^m. \tag{2}$$

If to fulfill action of all additional regulators on the output of the internal regulator, instead of n in parallel included to each regulator can find one regulator, which embracing parallel classic regulators and replacing the action of all additional regulators. But at the same algorithm of single regulator

becomes more complicated than the algorithm of each controller separately.

$$W_n''(s) = \frac{1}{s \cdot \sigma_n \cdot W_{okn}(s)} \cdot \frac{\sum (b_{mn} - a_{mn}) \cdot s^m}{\sum a_{nm} \cdot s^m} \cdot \prod_{k=n-1}^{1} \left(\frac{1}{s \cdot \sigma_k \cdot W_{okk}(s)} \cdot \frac{\sum b_{nk} \cdot s^n}{\sum a_{nk} \cdot s^n} \right) \tag{3}$$

All correction algorithms of dynamic processes contain derivatives do not less second-degree from error signal and therefore if there are noises in signal they will be affect the efficiency of such correction. In addition, if the control object's parameters changing that leads to instability of the characteristic frequencies in additional dynamic elements, so it is possible adjustment algorithms correction effective in only one operating loops point. Changing the number of added mass, leads does not to compensation of elastic vibrations by additional correction units, but to the vibrational increasing in control system. Therefore correction algorithms must be have the adaptation properties to the control object variable parameters.

In connection with the above we will look for the problem solving of elastic vibrations compensation in the systems regulation with consecutive correction by means of applying the fuzzy control principles for complicated objects, which include the presence of drive with elastic constraints in the transmission. This lets to preserve well-known advantages of systems with the dynamic parameters consecutive correction [12-16].

An approach based on the theory of fuzzy sets has a characteristic distinguishing features: in addition to the numeric variables are used fuzzy values, the so-called "linguistic" variables; a simple relationship between the variables described by fuzzy of utterances; complicated relationships are described by fuzzy algorithms [17]. This approach gives approximate, but at the same time effective ways for describe the systems behavior which are so complicated that for the dynamics correction require adaptive controllers with polynomials high degrees, as in the numerator as well as in the denominator.

To preserve the benefits of control systems with an active consecutive correction in parallel with the classic regulators include fuzzy controller, the functions of which will be to the suppression of vibrations arising in the control system due to the elastic vibrations in the transmission.

To the suppress in transmission elastic vibrations into the control loops foresee not only a signal proportional to the error between the reference and the actual value of a controlled magnitude as well as rate of change and the integral of the marked error, which corresponds to the fuzzy controller with PID dynamic characteristic. The structure of fuzzy controller foresees selection the input membership functions, rules processing terms, the finding of the output signal.

Synthesis of fuzzy controller rationally produce in two stages. At the first stage, fulfill selection of the membership functions number based on cluster analysis of the fuzzy controller input signal. At the second stage, based on adaptive neural network algorithms are found rules for processing terms.

The process of step-wise increase in motor speed from zero to the nominal level, the speed revers from nominal positive till negative nominal level, and then back from negative to positive nominal one, allows to create the most characteristic selection of variable data signals at the input and output of fuzzy controller, which are used to train the membership functions and rules for processing terms. This sampling values of the signals at the input and output of the fuzzy controller is supplemented by signals in the same operating modes, but with an step-wise change in load torque of the motor shaft.

Initial information for clustering is observation matrix of fuzzy controller input signals $\boldsymbol{D}$, which is formed according to the curves of the signal waveform at the input of a fuzzy controller

$$\boldsymbol{D}=\begin{bmatrix} E(t_1) & dE/dt\big|_{t1} & \int E\cdot dt\Big|_{t1} \\ E(t_2) & dE/dt\big|_{t2} & \int E\cdot dt\Big|_{t2} \\ \cdots & \cdots & \cdots \\ E(t_n) & dE/dt\big|_{tn} & \int E\cdot dt\Big|_{tn} \end{bmatrix}, \tag{4}$$

where $E(t)$– the error at regulator input.

These signals can be calculated analytically, using the found dynamic model of the control loop.

Each row of the matrix $\boldsymbol{D}$ represents the values of the three features of one of the objects of clustering for each controller, respectively proportional, differential and the integral parts. Clustering problem is to divide the objects in the matrix $\boldsymbol{D}$ on several subsets (clusters) in which objects are more similar to one another than to other clusters of objects. In a metric space "similarity" is determined by the distance. The distance is calculated as between initial object (with matrix lines $\boldsymbol{D}$), as well as from these objects to the clusters prototype. In this case, the coordinates of the prototypes are unknown - they are found at the same time with the partition of the data into clusters.

It is no any a priori assumptions, in the task solution, about the number of fuzzy clusters, therefore to find the number of clusters we using a subtractive clustering method is offered by R.Yager and D.Filev [18]. The method's idea is that each data point is allowed as a potential center of the cluster, then is computed measure of the ability to represent any point the cluster center. This quantitative measure based on the estimate of the density of data points near the center of the corresponding cluster.

According to this algorithm of the fuzzy clustering were computed value of the vector fuzzy controller input signal. The result of the calculation is shown in [12]. Number of centers clustering of determines the numbers of membership functions, that is, for the current regulator are necessary 4 of the membership functions, and for the speed controller only three ones.

Having determined the number of clusters for the input variables, perform the transition to the second stage of the synthesis of a fuzzy controller for this purpose use the training possibilities of artificial neural networks in order to find the output membership functions and the relative position of both input and output membership functions.

To find rule base according with the initial membership functions have been used the apparatus of hybrid networks in which the conclusion fulfill on based on fuzzy logic, but the corresponding membership functions are tuning on based on the algorithms of neural networks, the so-called adaptive neuro-fuzzy inference system (ANFIS) [19]. Such training system uses multiple input and output values and distributes the membership function according to the data vector $\boldsymbol{D}$. The membership functions parameters are changed in accordance with the given for training signals. These parameters calculations and their change is in accordance with the calculated gradient vector, which controls the deviation of the initial coordinates of the neural network of the specified value in the space provided for the training set of input / output data $\boldsymbol{D}$. For training taken backpropagation algorithm [20] as well as in combination with the least squares method together with the backpropagation algorithm. These algorithms allow to effectively be trained neuro-fuzzy controller from the data set at the input and output.

Fuzzy neural network consists of four neurons layers:

output nodes of the first layer are the numerical values of the membership functions in accordance with the values of the input signals;

outputs neuron of the second layer are truth degree of prerequisites the system knowledge base rules, which are calculated in accordance with expressions (knowledge base);

the third layer neurons fulfilling calculate values of the output membership functions;

single neuron of the fourth layer computes the output of the network.

Training of neuro-fuzzy network ANFIS type done under conditions:

the training epochs number accepted 100;

the number of input membership functions N;

training algorithms: back-propagation and a hybrid;

checked the membership functions: triangular, trapezoidal, generalized bell-shaped, Gaussian, double Gaussian, π-function, double sigmoidal, the product of two sigmoidal functions.

Based on the data of the errors of training, there is no need to take the input membership functions more complex than triangular or Gaussian.

To define the membership functions used typical Gaussian function

$$gaussmf(x,\sigma,c) = e^{-\left(\frac{x-c}{\sigma}\right)}, \tag{5}$$

where c - displacement; σ - width of the Gaussian function.

In the algorithms of the current and speed fuzzy controllers are sufficient to restricted with two components - proportional and differential. The output membership functions may used a zero-order Sugeno type.

From a comparison of the signals at the output of corresponding to real of fuzzy regulator and that it should reproduce follows that in times of appearance of free transition component (change of the reference-input signal at the loop's inputs) the output signal of fuzzy regulator corresponds to the desired signal only in sign, but not by value. In the moments of change reference-input signal the loop's dynamic substantially forms classic regulators of the active current and of the speed with suppression of circulating electro motive force (EMF). In the transition to the forced values of controlled variables real and the desired output voltage of the PD fuzzy regulator are well coincide. Thus in the forced mode the fuzzy regulator will significantly affect the dynamic processes in the control loops.

Transient analysis shows that the inclusion of a fuzzy regulator in parallel with classical one leads not only to increase the loops quick-action, but also to increase the overshoot compared to the optimum setting for modular optimum. In addition increasing overshoot at the moment of the second matching has result in increase in oscillation. To eliminate these adverse effects has been increasing the value of loop current's tuning coefficient from $a_T=2$, which should be for modular optimum to the value $a_T=3$, i.e. in one and half times that in the control system reduces quick-action till significance in tuning on module optimum. At the same time significantly reduces the overshoot and oscillation speed loop to values less than in tuning on module optimum.

For quantification comparison of the quality of transients was introduced the integral estimate I_K, which takes into account the rate of attenuation and the value of speed deviation in the aggregate. Have been calculated not only the speed deviation from reference-input level of x, but also to the third derivative including of the deviation speed

$$I_K = \int_0^{\infty} \left(x^2 + a_c \cdot a_T \cdot T_\mu \cdot \dot{x}^2 + a_c \cdot a_T^2 \cdot T_\mu^2 \cdot \ddot{x}^2 + a_c \cdot a_T^2 \cdot T_\mu^3 \cdot \dddot{x}^2 \right) dt . \qquad (6)$$

This assessment characterizes the approach of the transition to the extremal defined solution of the optimized loop motor speed characteristic polynomial differential equation

$$a_c \cdot a_T^2 \cdot T_\mu^3 \cdot \dddot{x} + a_c \cdot a_T^2 \cdot T_\mu^2 \cdot \ddot{x} + a_c \cdot a_T \cdot T_\mu \cdot \dot{x} + 1 = 0 . \qquad (7)$$

For a control rigid system take the value integral estimate I_K as base value with which compares all other values of this estimate.

The integral estimate I_K significances of the transition process indicator in the step-wise control mode and perturbation step-wise mode from the number of tubes attached to the drill string, depending on the dynamic characteristics of fuzzy controller were calculated for the jump of control and disturbance.

As follows from the analysis of received significances greatest difference from optimally tuned control system is seen in applying of PI fuzzy regulator, and least – in applying of PD fuzzy regulator. The interme-diate values of the control quality has PID regulator.

Conclusions. The carried out researches allowed to establish following regularities:

1. Replacement at the modernization process in the rotation mechanism thyristor DC drive on transistor AC drive with pulse-modulated impulse of autonomous voltage inverter will changes the dynamic characteristics of the whole electromechanical system, since in the latter case, increasing the bandwidth of electric drive control system is carrying out. The problem of drive system's frequencies compatibility with the drilling ring's dynamic parameters appears.

2. When the drilling depth increasing by three and a more tubes number, and increasing of the length of the proper drilling tube, brings to increasing of length drilling assembly, essentially reduces the own frequencies of polyresonance phenomena in mechanical part drilling assembly which in applying of AC drive gets in the bandwidth current loop and speed one.

3. The effective compensation in control loops the electromechanical, electromagnetic time constants and influence of the rotation EMF of the motor is possible by using classical regulators.

4. The quantitative and qualitative influence on the transition character of the elastic properties of the drill string to the current and the speed loops determined due the appearance in the object of loop current uncompensated dynamic unit with four poles and zeros in the transfer function and the speed loop – with two zeros and poles. Moreover, coefficients of the transfer function depend from tube weight, numbers of which varies according to the number associated tubes in drilling assembly that moves the poles and zeros of the transfer function in the complex plane.

5. The additional dynamic unit's dynamic properties compensation on the current loop dynamics in the field of classical regulators leads to the need for using a additional regulator with adaptive tun-

ing and the need to determine the derivatives up to the second order, that in the presence of noise in the signals of regulation will adversely affect the loop control process.

6. The introduction of fuzzy PD controller from error from the inputs of the proportional integral regulator speed and current to regulator's output, allows saving the advantages of active control systems with consequent correction and effectively suppressing fluctuations in the control system.

7. The quality of transients at various membership functions, does not change significantly therefore it is advisable to choose a triangular or Gaussian membership function through their ease of implementation.

8. The output membership functions must be chosen such as zero-order Sugeno type, because of the linearly varying functions poorly suppressed by the elastic vibrations in the control system.

9. Fuzzy regulator badly reproduces necessary output signal with rapid change reference signal and the perturbing signal the beginning of each step-wise action, when classical regulators compensates the inertial influent of electromagnetic and electro-mechanical time constants. When the control systems working in forced mode where is not working effectively the classical regulators, and at this mode the fuzzy regulator effectively suppresses the elastic vibrations. Thus is carried out temporary selection of classical and fuzzy regulators operation mode.

10. In the absence of the oscillatory component of elastic vibrations in the signals of the control system, the fuzzy controller does not influence the dynamics of the control system.

11. Changing the natural frequencies of elastic vibrations drill string does not significantly affect the quality of transients, if the tuning is made of a fuzzy regulator to compensate for elastic vibrations with minimum tubes number at drill string.

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